

Dark Matter: Looking for WIMPs in the Galactic Halo

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Abstract. Overwhelming observational evidence indicates that most of the matter in the Universe consists of non-baryonic dark matter. One possibility is that the dark matter is Weakly-Interacting Massive Particles (WIMPs) that were produced in the early Universe. These relics could comprise the Milky Way's dark halo and provide evidence for new particle physics, such as Supersymmetry. After reviewing some of the evidence for dark matter and the WIMP hypothesis, I will describe the strategy for searching for WIMPs, along with a survey of the current status and outlook. In particular, dark matter searches have begun to explore the region of parameter space where SUSY particles could provide dark matter candidates. I will also mention some of the recent theoretical work on dark matter candidates which is being done in anticipation of the turn-on of the LHC and as part of the active R&D on the ILC. Finally, a vigorous detector development program promises significant advances in WIMP sensitivity in the coming years.

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1. DARK MATTER AND THE WIMP HYPOTHESIS

A broad range of observations from the rotation speeds of stars in ordinary galaxies to the gravitational lensing of superclusters tell us that 80–90% of the matter in the universe is in some new form, different from ordinary particles, that does not emit or absorb light. Cosmological observations, especially the Wilkinson Microwave Anisotropy Probe (WMAP) of the cosmic microwave background radiation [2], have provided spectacular confirmation of the astrophysical evidence. The resulting picture, the so-called “Standard Cosmology,” finds that a quarter of the energy density of the universe is dark matter and most of the remainder is dark energy [1]. A basic foundation of the model, Big Bang Nucleosynthesis, tells us that at most about 5% is made of ordinary matter, or baryons. The solution to this “dark-matter problem” may therefore lie in the existence of some new form of non-baryonic matter. With ideas on these new forms coming from elementary particle physics, the solution is likely to have broad and profound implications for cosmology, astrophysics, and fundamental interactions.

A generic class of particles that would have been produced in the early universe at the dark matter density — if suitable candidates exist — are the so-called Weakly Interacting Massive Particles, or WIMPs. The idea was first put forward by Lee and Weinberg [3] that massive particles (GeV–TeV scale) with annihilation cross sections on the scale of the Weak Interactions would fall out of equilibrium with ordinary matter and, if stable, survive as thermally produced relics. In the context of the dark matter problem, it was realized that SUSY particles (as well as other extensions to the Standard Model) lead to candidates that would freeze out in this way and could be detectable today [5, 4] if they

make up the dark matter in the Milky Way’s galactic halo.

Figure 1a shows the standard “progress” plot in this field, in which the elastic cross section normalized to the nucleon is plotted against the WIMP mass. Theoretical regions for specific models sample appropriate regions of parameter space, including WMAP constraints of the relic density, known accelerator bounds on particle parameters, as well as specific imposed constraints that define the model, *e.g.*, minimal Supergravity which assumes a high degree of degeneracy in the SUSY masses and couplings. Other than the unconfirmed claim by the DAMA collaboration, which observes an annual modulation expected due to seasonal kinematic variations corresponding to the heart-shaped 3σ contour [6], experimental upper limits are shown as curves that exclude the parameter space above them at 90% C.L.. That is, cross sections higher than a given limit curve would have been observed in the given experiment. Further experimental bounds are shown below in Figure 1b. The scaling to the nucleon cross section is generally assumed to scale with the nuclear mass number since in most models the cross section is dominated by coherent scalar interactions among the nucleons. Other possibilities such as spin-dependent interactions are also considered, the strength of which tend to be dominated by unpaired neutrons or protons in the target nucleus; for a general discussion see [4], and also [12] for a more recent update.

In the coming few years, the turn-on of the LHC and the advance of direct searches will begin to search some of the same SUSY parameter space. It is worth emphasizing that unraveling the nature of dark matter will require a combination of these approaches (with possible input also from “indirect” astrophysical searches for sources of WIMP annihilation products). Accelerator experiments can pin down the mass and couplings of a WIMP candidate but cannot directly establish its stability or that it is physically present. Direct astrophysical searches can establish that particles are present in the halo, but are sensitive to the elastic cross section, which is not sufficient to calculate the relic density. Positive detections from both approaches should be sufficient, however, to determine that both are seeing the same stuff, and to arrive at a comprehensive solution to the dark matter problem. It is also interesting to note that the astrophysical searches themselves are more sensitive to quantities that inform the fundamental particle physics, *e.g.*, the elastic cross section determined by a direct search provides information on the neutralino mixing angles, which are difficult to determine from, say, the LHC in some benchmark models [13].

2. SEARCHING FOR DARK MATTER

If WIMPs are indeed the dark matter, their local density in the galactic halo inferred from the Milky Way’s gravitational potential may allow them to be detected via elastic scattering from atomic nuclei in a suitable terrestrial target [5]. Owing to the WIMP-nucleus kinematics assuming a WIMP RMS-speed of about 220 km/s (typical of bound objects in the halo), the energy transferred to the recoiling nucleus is on the order of 10 keV [14]. The expected rate of WIMP interactions, which is already limited by observations to less than 0.1 events/kg/day [15], tends to be exceeded in this energy range by the rate of interactions from natural radiation. Therefore, WIMP search experiments must be located deep underground for protection from cosmic rays, made of high purity materials with

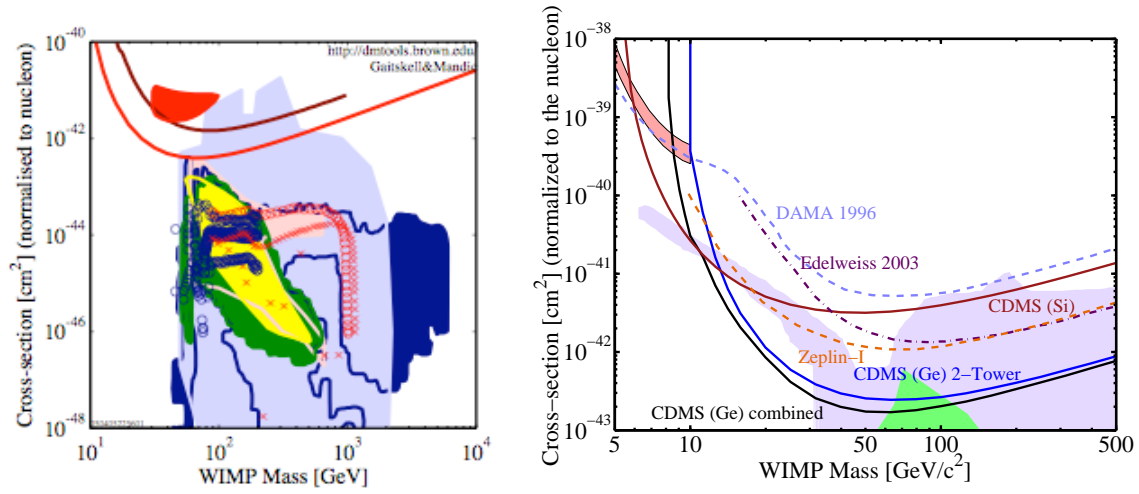


FIGURE 1. (a) Left: The plot of WIMP-nucleon cross section versus WIMP mass includes various theoretical predictions for different SUSY models, including “Split Supersymmetry” (circles [7, 8]), post-LEP LHC Benchmarks (X’s [9]), and minimal supergravity with and without the muon $g-2$ constraint (medium grey and black; [10]). The closed contour at upper left is the DAMA annual modulation signal [6]. For illustration, some experimental bounds are shown: the upper from EDELWEISS [21] and the lower from CDMS’s 2003 data [11]. (b) Right: On a reduced scale, this version shows the present state of experimental bounds for 90 % C.L. limits on the WIMP-nucleon scalar cross section. The upper CDMS Ge curve uses only the most recent data of 34 kg-days [15]; the lower Ge curve includes data from the previous run [16]. Supersymmetric models allow the largest shaded region [17], and the smaller shaded region [18]. The shaded region in the upper left is a sodium-recoil interpretation [20] of the DAMA NaI claim, and experimental limits are from DAMA [19], EDELWEISS [21], and ZEPLIN [23].

low natural radioactivity, and have the ability to reject residual backgrounds.

A common technique to accomplish this background rejection is to use so-called “recoil discrimination.” The WIMP mass is well-matched kinematically to depositing energy on the order of 10 keV to an atomic nucleus in a detection medium. On the other hand, the dominant sources of background are electromagnetic, namely, gammas and betas from uranium and thorium decay chains, environmental radon, potassium-40, etc. Since these backgrounds deposit energy in the electrons in the detection medium, discriminating between, say, a recoiling germanium or xenon nucleus with 10 keV versus a 10 keV electron from a Compton scatter is an important tool for defeating the background.

Also taking into account the relatively low rate of WIMP-induced recoils, and the intrinsic inability of a detector to discriminate between neutrons and WIMPs, as well as other issues pertaining to the signal, the desirable characteristics of a dark matter experiment follow:

- High purity to minimize residual background.
- Recoil discrimination to reject residual background.
- Great depth to minimize cosmic-ray related backgrounds, primarily high-energy neutrons produced by unvetted muon interactions in the cavern walls, because

neutrons with energy above 50 MeV are difficult to shield.

- Large instrumented detector mass to maximize the interaction rate. Good statistics on the signal also allow for the study of a secondary characteristic of the signal, that of seasonal modulation due to a kinematic effect from the Earth's variation between prograde and retrograde motion with respect to the Sun's orbit about the Galactic center.¹
- Low energy threshold, also to maximize the rate, given that the nucleus's recoil energy spectrum is roughly a falling exponential.
- Position information of the event interaction, since some backgrounds tend to come from surfaces, and also WIMPs will interact isotropically.
- Information on the recoiling nucleus direction, because the Earth's rotation combined with a preferred direction of the lab's velocity vector with respect to the Galaxy, results in a diurnal modulation in the incoming WIMP "wind" direction.

3. DARK MATTER EXPERIMENTS: CDMS

In this section, I discuss the methods and results obtained by the Cryogenic Dark Matter Search (CDMS) Collaboration, of which I am a member and which currently has the world-leading sensitivity. In section 4, I survey some of the other techniques and experiments that are under way or under development, which will illustrate the both the broad range of approaches to meet the criteria described above and the great level of activity aimed at detecting dark matter.

The primary distinction of the CDMS experiment is our novel ionization and athermal-phonon detectors, which provide detailed information about each event. A key parameter, the "ionization yield," is determined for each event through the simultaneous measurement of an ionization signal and a phonon-mediated signal, and is defined as the ratio of the ionization signal per unit recoil energy. Recoil energy is determined by the phonon signal with a correction for the phonons produced by the drifting ionization. The ionization yield is useful because nuclear-recoil events have typically a one-third lower yield than electron recoils, as is illustrated in Figure 2. The discrimination power is well demonstrated by exposing the detector to gammas and neutrons.

Briefly, the detectors consist of 1-cm-thick 3-inch-diameter germanium or silicon puck-like cylinders upon which metals are photolithographically deposited. The electrode structures collect the ionization signal in a standard capacitor-like geometry. The phonons are collected by superconducting aluminum quasi-particle traps which in turn funnel the broken Cooper pairs into thin superconducting tungsten meanders. The tungsten meanders are maintained in the middle of their 80 mK superconducting transition with a stable voltage bias. Events are sensed by change in the film resistance, which results in a current signal coupled to a SQUID amplifier. To maintain appropriate operating temperature, the detectors are operated in a shieldable cryostat at a temperature of

¹ This effect has been observed by the DAMA collaboration, resulting in the contour of Figure 1a, but remains controversial and contested by other searches.

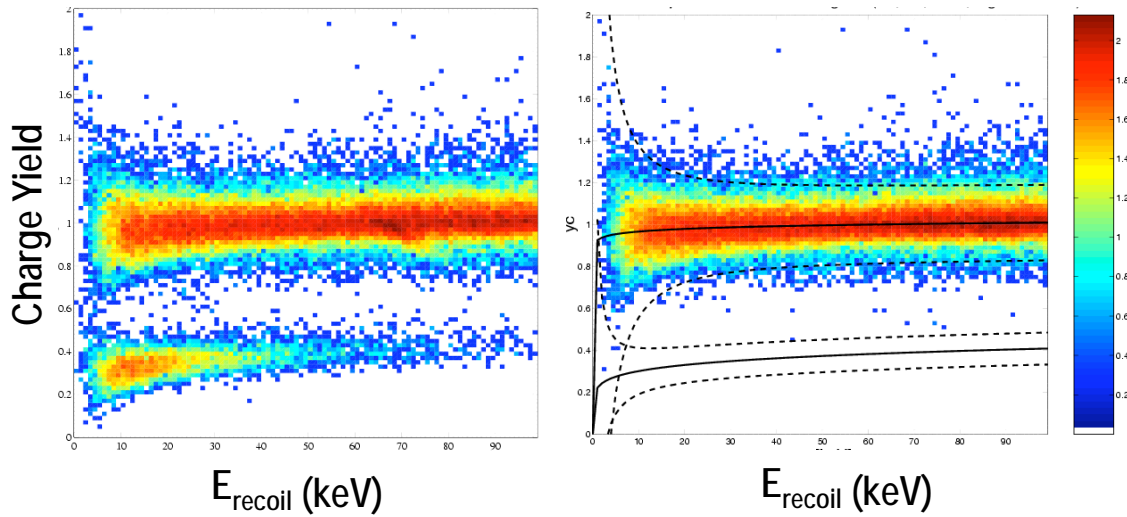


FIGURE 2. These scatter plots of yield versus recoil energy illustrate the discrimination capability of the detectors when exposed to gamma + neutron source (^{252}Cf) on the left and gammas only (^{60}Co) on the right. The plot on the right contains over 50,000 events in the “gamma” band, none of which is falsely identified as a nuclear recoil event in the lower “neutron” band.

50 mK. The shield consists of lead shielding for gammas, polyethylene for moderating neutrons, and scintillator to tag muon-coincident events.

While the ionization yield is effective at rejecting electron recoils in the bulk, betas that have energy in the range of WIMP recoils are not very penetrating and suffer a reduced yield in a few-micron-thick “dead layer” typical of semi-conductor ionization detectors. Fortunately, this loss of yield, which can cause a false-positive nuclear recoil, is compensated by a difference in pulse shape between surface events and bulk events owing to the differing phonon propagation velocities of the two types of events. This effect is illustrated in Figure 3, which shows the onset of the phonon pulse relative to the prompt ionization signal (or “start time”) versus the ionization yield.

Experiment runs in the underground setup in the Soudan Mine in 2003 and 2004 resulted in total exposures in germanium after cuts of 53 kg-days. No events above estimated background were observed, where background expectations were less than one event in each of the two exposures. (See [15] and references therein for a complete discussion.) These data led to the limits on the WIMP-nucleon cross section for spin-dependent couplings shown in Figure 1b. In addition to ruling out some regions of SUSY parameter space, these limits contradict the claim by DAMA [6] assuming a standard halo and couplings.

4. A SURVEY OF SOME OTHER TECHNIQUES

Some of the other leading experiments searching for dark matter use recoil discrimination techniques and cryogenic detectors similar to CDMS. The EDELWEISS collaboration also uses a combination of ionization and phonons, but the phonon signal is purely

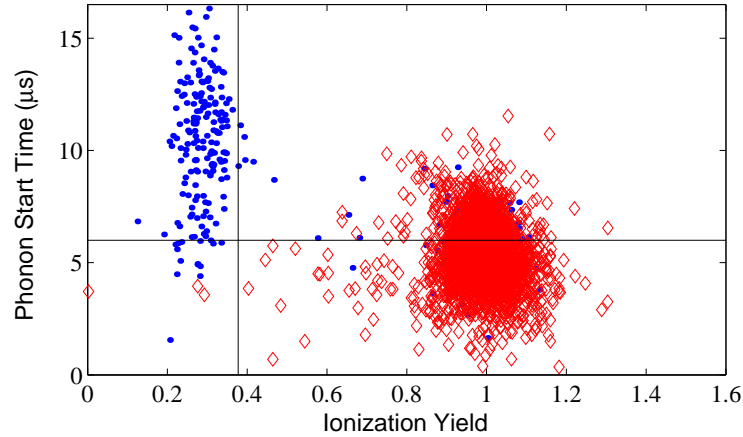


FIGURE 3. This plot of start time versus yield shows the improved 2-parameter discrimination between gamma-induced events from ^{133}Ba calibration (diamonds), including a tail of surface events, and neutron induced events from ^{252}Cf (dots). The two lines define the approximate acceptance region for nuclear recoils (upper right) with high rejection of both bulk and surface gamma-induced electron recoils.

thermal (based on NTD thermistors), and so there is no discrimination between bulk and surface events in the thermal channel. Instead, the focus of that group has been to emphasize minimizing the effects of the dead layer by experimenting with different types of charge contacts. While some progress was made, the performance limitations have led to them to pursue highly-resistive metal contacts that promise some surface discrimination in the thermal signal. The limit set by EDELWEISS's 2002/2003 was a then-best result [21], and is shown in Figure 1b.

The CRESST collaboration uses cryogenic detectors as well, but instead of ionization as the second parameter, they use scintillating substrates and the ratio of light to charge to discriminate the type of recoil. The thermal signal from the calcium tungstate (CaWO_4) targets are read out with a tungsten superconducting thermometer, and the light signal is absorbed and converted to heat in a second thin crystal with a similar read out. Limits from their 2004 data show a neutron background, which was identified with the oxygen recoils. Under that interpretation, that is, in which no nuclear recoils are attributed to the tungsten nuclei, the resulting limit [22] is similar to the limit curve of EDELWEISS.

Liquid nobles, namely, neon, argon and xenon are all generating interest as dark matter detectors. Several programs to develop new detectors are underway, and one, the Zeplin collaboration, has produced a limit (again, see Figure 1b on the cross section [23]). This limit is based on the Zeplin-I detector, which detects scintillation pulses in liquid xenon. The scintillation light arises from the deexcitation of a complex series of singlet and triplet excimers and dimers, with somewhat different decay times. Owing to the different energy density of electron and nuclear recoils, there is some pulse-shape discrimination between the two event types. Looking forward, there are two promising avenues. In xenon, the work is aimed at using a secondary ionization signal to combine with the primary scintillation light as a discrimination parameter. In argon and neon, the time constants between the triplet and singlet states are much larger than in xenon, and

so pulse shape discrimination of the primary scintillation should make a good parameter. Indeed, this has already been demonstrated at relatively high energy, and work is now trying to characterize the performance at lower thresholds.

A completely different approach to gaining immunity to electromagnetic backgrounds is the revival of the bubble chamber by the COUPP Collaboration [24]. The idea here is to operate the chamber in a thermodynamic regime in which the lower energy density tracks from electron recoils and minimum ionizing radiation are insufficient to nucleate bubbles, but where the higher energy density recoils of nuclei are above the nucleation-energy threshold. A technical challenge, which has been met, was to passivate the walls of the vessel so that microcracks in the walls were not a cause of spontaneous nucleations, allowing the chamber to remain stable. The present configuration of the experiment is a 2-kg CF_3I bubble chamber being setup in a modest-depth site in the MINOS near-detector gallery at Fermilab for a demonstration test.

Finally, as mentioned earlier, it is possible to establish the galactic origin of a signal if the direction of the recoil nucleus can be detected. The only demonstrated method of performing such a measurement has been in the low-pressure TPC technology developed by the DRIFT collaboration [25]. In this device, recoiling nuclei ionize the TPC gas in the presence of CS_2 , which is highly electronegative. The CS_2 negative ions that form are drifted through the gas to read out MWPC's with very little diffusion and so the primary ionization track is preserved. Also, a measure of the ionization per unit pathlength is a good identifier of the recoil type. Unfortunately, to match the physical size of the track with the position resolution of the read out, the chamber must be run at low pressure (about a 1/20th of an atmosphere) and so a very large target volume is required. Furthermore, to have sufficient statistics to observe the diurnal modulation in the directional distribution of the tracks, on the order of a hundred detected events is needed [26]. This presents a daunting challenge, since the cross section is not even known. However, ongoing R&D is attempting to address this challenge with superior read out schemes. For example, the required statistics are reduced approximately by a factor of ten if the head of the track can be identified.

5. SUMMARY AND OUTLOOK

The outlook for WIMP detection looks very promising. Following more than a decade of detector development in cryogenic detectors, significant strides have been made in sensitivity. The challenge to cryogenic detectors, which I believe we will be able to meet with sufficient R&D efforts, is to continue scaling the detector mass; clearly the technology itself performs extremely well with regard to background rejection. Within the CDMS collaboration, the technology is already capable of an additional factor of ten at Soudan, and plans for a "SuperCDMS" 25-kg experiment for a factor beyond that have been proposed. Plans for further scale up and cryogenic detector improvements are also underway among the CRESST and EDELWEISS collaborations. On the liquid nobles front, intensive efforts are being brought to bear and we should see some important technology demonstrations in the coming year or two, in particular by the XENON, ZEPLIN and XMASS groups using xenon, and the DEAP and WARP collaborations using argon and/or neon. The COUPP bubble chamber, and also the

PICASSO experiment, are using innovative techniques based on superheated liquids, for background immunity.

The advancing of this work, and the possibility of producing WIMP candidates in the lab as the LHC era begins, offer the potential for much exciting science as we attempt to unravel the nature of dark matter.

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REFERENCES

1. For a more detailed discussion of these ideas, see also Mark Trodden's contribution to the conference in these proceedings.
2. D.N. Spergel et al. (WMAP collaboration), *Astrophys. J. Suppl.* **148** 175 (2003).
3. B.W. Lee and S. Weinberg, *Phys. Rev. Lett.* **39**, 165 (1977).
4. G. Jungman, M. Kamionkowski, and K. Griest, *Phys. Rep.* **267**, 195 (1996).
5. M.W. Goodman and E. Witten, *Phys. Rev.* **D31**, 3059 (1985).
6. R. Bernabei et al. (DAMA Collaboration), *Phys. Lett.* **B480**, 23-31 (2000); R. Bernabei et al., astro-ph/0405282.
7. N. Arkani-Hamed and S. Dimopoulos, hep-th/0405159.
8. G.F. Giudice and A. Romanino, hep-ph/0406088.
9. J. Ellis, K. A. Olive, Y. Santoso and V.C. Spanos, *Phys. Lett.* **B565**, 176-182 (2003).
10. E.A. Baltz and P. Gondolo, hep-ph/0407039.
11. D.S. Akerib et al. (CDMS Collaboration), *Phys. Rev. Lett.* **93**, 211301 (2004).
12. C. Savage, P. Gondolo and K. Freese, *Phys. Rev.* **D70**, 123513 (2004).
13. E.A. Baltz, M. Battaglia, M. Peskin, and T. Wizansky, in preparation (private communication); see also, <http://www.physics.syr.edu/~trodden/lc-cosmology>.
14. J.D. Lewin and P.F. Smith, *Astropart. Phys.* **6**, 87 (1996).
15. D.S. Akerib et al. (CDMS Collaboration), *Phys. Rev. Lett.* **96**, 011302 (2006).
16. D.S. Akerib et al. (CDMS Collaboration), *Phys. Rev. Lett.* **93**, 211301 (2004).
17. A. Bottino et al., *Phys. Rev.* **D69**, 037302 (2004).
18. J. Ellis et al., *Phys. Rev.* **D71**, 095007 (2005).
19. R. Bernabei et al. (DAMA Collaboration), *Phys. Lett.* **B389**, 757 (1996).
20. P. Gondolo and G. Gelmini, *Phys. Rev.* **D71**, 123520 (2005).
21. V. Sanglard, et al. (EDELWEISS Collaboration), *Phys. Rev.* **D71**, 122002 (2005).
22. G. Angloher, et al. (CRESST Collaboration), *Astropart. Phys.* **23**, 325-339 (2005).
23. G.J. Alner et al. (UK Dark Matter Collab.), *Astropart. Phys.* **23**, 444 (2005).
24. W.J. Bolte et al. (COUPP Collaboration), astro-ph/0503398.
25. D.P. Snowden-Ifft, C.J. Martoff, J.M. Burwell, *Phys. Rev.* **D61**, 101301 (2000).
26. C.J. Copi, L.M. Krauss, D. Simmons-Duffin, S.R. Stroiney, astro-ph/0508649.